PROC. R. SOC. VICT. vol. 95, no. 4, 205-225, December 1983

PALAEOZOIC ACID VOLCANISM IN VICTORIA

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'. . . *something of the nature of a cataclysm of lavas, mainly acid, must have overwhelmed Victoria in Upper Devonian times'* (E. S. Hills, 1932)

Abstract: Although the limits of the major belts of 'dacites' in central Victoria, and acid-intermediate rocks elsewhere were established by the early 1900s, it wasn't until E. S. Hills commenced work in the Cathedral Range area in 1928 that the age relationships were clarified. Following his discovery of a Late Devonian fish fauna between the basement sediments and the main volcanic units in the Cerberean Cauldron, Hills worked extensively in the region for the next 30 years, eventually concluding that a mechanism of cauldron subsidence enabled the eruption and emplacement of the acid volcanic rocks in most of the Central Victorian complexes. Since the 1960s, debate has concentrated on the role of ash flows, as distinct from lavas, in the emplacement of large volumes of acid volcanic rocks. However, there was no general discussion, let alone agreement, on the Victorian occurrences until the 1970s.

This paper reviews the contribution made by early geologists, culminating in the work of Skeats and Hills, towards the current knowledge of acid volcanism in Victoria. The development of the concept of ash-flows and their association with large-scale subsidence complexes is discussed. The features of the main belts of acid-intermediate rocks in Victoria are outlined, their chemical and mineralogical characteristics summarised and a possible model for the origin of the magmas presented.

In 1980, Mt. St. Helens, Washington, provided a yardstick for the awesome power of explosive volcanism. However, even this eruption and its devastating effects pale into geological insignificance when compared to volcanic activity which occurred in the Victorian region during the Late Devonian. Here, over a period possibly as short as 3-5 million years, some of the most spectacular eruptions and simultaneous crustal displacements ever to affect a relatively small area of the earth's crust took place. And the evidence for these events is remarkably well preserved in a number of subsidence complexes in Central Victoria (Fig. 1).

HISTORICAL SUMMARY

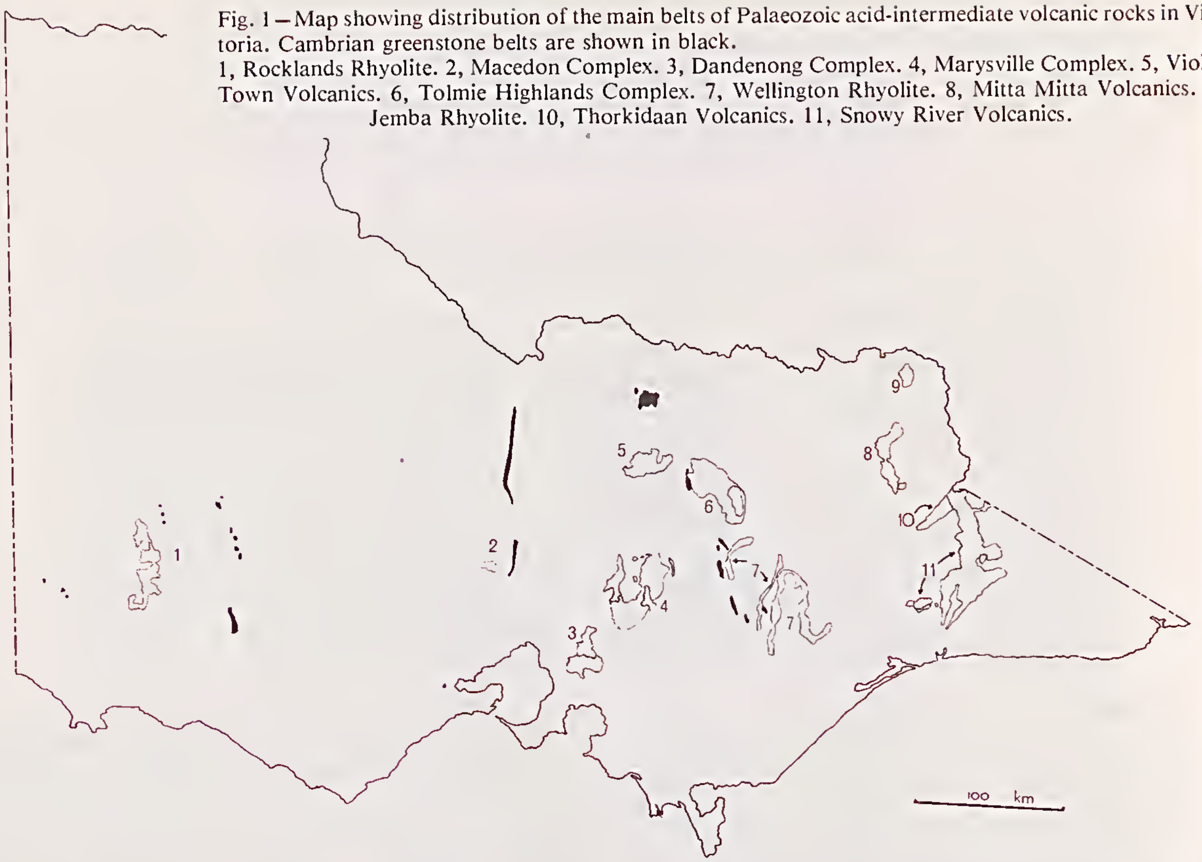
Edwin Sherbon Hills may well have been drawn to the Cathedral Range area, 80 km north east of Melbourne, in early 1928 as much by its scenic and geomorphological qualities as by the suggestion from Professor E. S. Skeats that here the relationship between the Cathedral Beds (then believed to be Late Devonian or Early Carboniferous) and the supposed Early Devonian 'dacites' may be revealed. Skeats had maintained an interest in the 'dacite' problem and was instrumental in establishing a degree of order to the diverse geological data accumulated since the 1850s (Skeats 1909, 1910).

As early as 1854, Selwyn had regarded the 'Palaeozoic Traps' of the Melbourne region as intrusive on the basis of what seemed to be gradational contacts with granitic rocks. This interpretation (e.g. Murray 1895) persisted until the early 1900s; for example, extensive areas of rocks now known to be volcanic units were shown as granite on the 1902 Geological Map of Victoria (8 miles to inch). In the east of the State, an extensive belt of acid volcanic rocks, the 'Snowy River Porphyries' had been broadly delineated by Howitt (1876) with subsequent contributions from Murray (1877, 1887), Whitelaw (1899) and Ferguson (1899). Kitson (1899) correlated acid volcanic rocks near Whitfield (now the Tolmie Highlands Complex) with the Snowy River Porphyries. In the first detailed investigation of a Central Victorian volcanic complex, Gregory (1902) concluded that the Mt Macedon 'dacite' was volcanic and assigned an age between early Mesozoic and early Cainozoic. Petrographic and mineralogical similarities prompted Gregory to conclude that the Macedon 'dacites' were related to those known from the Dandenongs, Healesville and the Cerberean Ranges. Skeats and Summers (1912) reinforced Gregory's claim for such a relationship, but overturned some of his other conclusions. In western Victoria, Dennant (1893) partially described the occurrence of 'quartz porphyries' in the Hamilton-Cavendish-Balmoral area. The acid series of volcanic rocks ('felsites', 'quartz felsites') in the Mt. Wellington area of Gippsland was described by Howitt (in Murray 1877, 1891).

So, by the early 1900s, most of the acid volcanic belts in Victoria had at least been delineated, even if petrographic, geochemical and stratigraphic information was virtually non-existent. However, major problems remained unresolved; the general relationship between the 'dacites' and granodiorites of central Victoria was uncertain, and the age of the complexes themselves was subject to debate.

Credit for the first broad review of these problems concerning acid volcanism in Victoria should go to Skeats (1909) who drew a distinction, mainly on petrographic and geographic grounds, between the 'Snowy River Porphyries' and the 'Dacite and Quartz-Porphyrite Series' of central Victoria. Both series he

Fig. 1 — Map showing distribution of the main belts of Palaeozoic acid-intermediate volcanic rocks in Victoria. Cambrian greenstone belts are shown in black.
1, Rocklands Rhyolite. 2, Macedon Complex. 3, Dandenong Complex. 4, Marysville Complex. 5, Violet Town Volcanics. 6, Tolmie Highlands Complex. 7, Wellington Rhyolite. 8, Mitta Mitta Volcanics. 9, Jemba Rhyolite. 10, Thorkidaan Volcanics. 11, Snowy River Volcanics.



placed in the Early Devonian. This age for the Snowy River Porphyries was reasonably well established by palaeontological controls (Skeats 1909, Howitt 1890), but the argument for a similar age for the central Victorian complexes was somewhat circular. The volcanic rocks were clearly younger than the 'Silurian' and Ordovician basement sediments, the sequence in the Tolmie and Toombullup Ranges was overlain by Carboniferous sediments (Summers 1908) and the granodiorites, which were generally accepted as Devonian, were slightly younger than the 'dacites', based on contact relationships in the Dandenongs and at Mt. Macedon.

Skeats had drawn on widespread evidence to establish the relationship between 'dacite' and granodiorite. Even so, some ambiguity persisted over the nature of the dacite itself, as Skeats admitted 'I think a good deal of the Marysville dacite must be regarded as intrusive rather than effusive'. Given the very coarse-grained recrystallisation textures exhibited by some of the units, such a view may be excused in the absence of detailed stratigraphic information at that time. Somewhat prophetically, Skeats observed that the 'dacites' in the Dandenong and Strathbogie Ranges and at Narbethong and Marysville, passed, without sharp junction, into 'quartz porphyries' or 'quartz porphyrites'. The significance escaped Skeats at the time, but the mineralogical gradation between major volcanic units was later to prove important in enabling Hills to establish the age of the 'dacites'.

The Role of E. S. Hills

Hills essentially set out in 1928 to solve an age relationship problem. This he accomplished quickly, showing that a strong unconformity existed between the overlying volcanic rocks and the Cathedral Beds, which he placed high in the Late Silurian.

Discovering that a series of acid lavas, basalts and sediments occurred on the slopes of the Blue Range, immediately east of Cathedral Range, he mapped them for a strike distance of about 10 km and established the first generalised sequence (Table 1) in what was to become known as the Cerberean Cauldron. Hills then found a fossiliferous sequence of lacustrine sandstones and shales, between the basal conglomerate to the volcanic sequence and the main rhyolite (Rhyolite α) forming the summit of the Blue Range near Taggerty. These 'Taggerty fish beds' established a Late Devonian age which enabled Hills to confidently state that the volcanic rocks in the Cathedral district were Late Devonian (Hills 1929a). Hills was the first to break free of the early attempts to 'pigeon hole' all the volcanic rocks into the Early Devonian. However, the argument for extensive Late Devonian volcanism in Victoria required a further step, namely determination of the relationship between the volcanic sequence at Taggerty and the more

TABLE 1
HISTORICAL DEVELOPMENT OF THE CORRELATION OF SEQUENCES WITHIN THE CERBEREAN AND ACHERON CAULDRONS

Taggerty (Hills, 1929)	Marysville (Hills, 1929)	Marysville (Hills, 1932)	Eildon (Thomas, 1947)	Cerberean Cauldron (general) (Hills, 1959)		Cerberean Cauldron (general) (Birch et al, 1970) (for details, see McLaughlin, 1976; Table 5.1)	Acheron Cauldron Hills (1959)	Acheron Cauldron Dudley et al (1971)
		Adamellite Granodiorite (Hybrid rocks)	Ring Dykes	Granodiorite, Adamellite Ring Dyke	MARYSVILLE GROUP Intrusive Phase	<u>Central Intrusion</u> <u>Ring and Radial Dykes</u>		
					Collapse Phase	<u>Acheron Volcanics</u> (not represented)	Hypersthene dacite Hyp-bio-rhyodacite	<u>Alcheron Volcanics</u> Donna Buang Rhyodacite Warburton Rhyodacite
Rhyolite α	Rhyolite α	Rhyodacite Toscanite Nevadite	<u>Upper Acid Flows</u> Qtz-biotite-hyp-rhyodacite Nevadite-toscanite } Cordierite Nevadite }	<u>Cerberean Volcanics</u> 'Snobite' (hybrid) } Bio-hyp-rhyodacite } Toscanite } Nevadite }	Collapse Phase	<u>Cerberean Volcanics</u> Lake Mountain Rhyodacite Rubicon Rhyolite	Biotite dacite } variants Quartz dacite } Nevadite	<u>Cerberean Volcanics</u> Lake Mountain Rhyodacite Rubicon Rhyolite
Rhyolite β	Rhyolite β		<u>Toscanite Series</u> Fragmental Toscanite Middle Rhyolite Tuffs	<u>Taggerty Group</u> Fragmental acid Volcanics (ignimbrites)	TAGGERTY SUBGROUP (PreCollapse)	<u>Robleys Spur Volcanics</u> Rhyodacites (= Fragmental toscanites) Rhyolite (= Middle Rhyolite) Andesites, tuffs	Andesite xenoliths in later flows	<u>Robleys Spur Volcanics</u> Rhyodacite Rhyolite Diamictites Andesites
Melaphyre	Andesite? Melaphyre	Meta-basalts Meta-andesites shales etc.	<u>Basic Series</u> Basalts and andesitic basalts Ashes, tuffs	Basic volcanics (basalts, andesites)	TAGGERTY SUBGROUP (PreCollapse)	<u>Torbreck Range Andesite</u> Basaltic andesites, tuffs		
Tuffs and fossiliferous sediments	Tuffs (barren)		Thin tuff	Shales and Sandstones with fish and plant remains	TAGGERTY SUBGROUP (PreCollapse)	<u>Blue Range Formation</u> Shales, sandstone with fish and plant remains; tuffs etc.		Not represented
			<u>Lower Acid Series</u> Tuffs Biotite rhyodacite & tuffs Rhyodacite Rhyolite	<u>Snobs Creek Volcanics</u> Biotite Rhyodacite Rhyodacite Rhyolite	TAGGERTY SUBGROUP (PreCollapse)	<u>Snobs Creek Formation</u> Biotite-rich rhyodacite & tuff Rhyodacite Rhyolite	Soda Rhyolite (N.B. this is the sodium-enriched basal phase of the Rubicon-Rhyolite near Warburton)	
Basal conglomerate	Basal conglomerate	Basal conglomerate	Basal conglomerate thin seds.	Basal conglomerate		Wightmans Hill Conglomerate		
Silurian (Cathedral Beds in part)	Silurian	Silurian	Silurian/Lower Devonian	Unconformity		Siluro-Devonian sedimentary Cathedral & Koala Ck. Sst in part		

widespread 'dacites'. The sequence of volcanic rocks, tuffs and sediments at Taggerty was actually the second piece of a jigsaw puzzle which was to take nearly 55 years to complete. In 1915, Junner had mapped part of a similar volcanic sequence near Narbethong, nearly 30 km south of Taggerty. In the Marysville-Cumberland region, east of Narbethong, Hills clearly showed that rhyodacite ('dacite') overlay the main rhyolite ('nevadite') which he traced along strike and confirmed as his Rhyolite α at Taggerty (Hills 1929b, 1932). It was however, impossible to map a boundary between the two rock types as they merged through continuous vertical mineralogical variation, a feature alluded to previously by Skeats. This continuity could only mean that no great age difference existed between the two and hence the Marysville 'dacites' must have been Late Devonian.

Hills then argued, as others before him had done, that the close similarity between the Marysville 'dacites' and those at Macedon, Lilydale (Dandenong Ranges), the Strathbogies and Tolmie (Tolmie Highlands) was good evidence for an identical age, now shown to be Late Devonian, for all. This prediction has since been confirmed by radiometric dating techniques (McDougall *et al.* 1966, Richards & Singleton 1981).

Perhaps surprisingly, nearly thirty years separate Hills' 1932 paper and his 1959 discussion on the relationships between acid magmatism and crustal fracturing in southeastern Australia. Hills' treatment of the topic was to discuss individual complexes in the region, with the greatest prominence being given to the Cerberean Cauldron. He did however, examine the structure of the Dandenong Ranges Complex in 1941, but made no reference to the mechanism of emplacement. It is clear that Hills spent the interval of twenty-seven years fruitfully, not only by encouraging others to investigate similar complexes in central Victoria (e.g. D. A. White in the Strathbogies, D. E. Thomas at Eildon), but also by continuing his own tasks of mapping the volcanic sequence in the Cerberean Ranges and preparing a monograph. He also wrote two short papers, one on myrmekite (Hills, 1933), the other on oscillatory zoning in plagioclase (Hills, 1936), both based on observations made on feldspars in the 'nevadite-dacite' sequence at Marysville.

It was not until after his 1935 review of the Victorian Devonian (Hills 1935) that Hills became aware of the possibility that the volcanic sequence between Taggerty and Marysville was part of a cauldron subsidence structure, with a surrounding ring dyke. During the 1940s and 1950s, Hills tested this hypothesis by mapping the whole Cerberean complex. Although most of this must have been at a reconnaissance level, particularly on the eastern side of the ranges (where Whitelaw, on an earlier (1913) unpublished map, had shown parts of the eastern ring dyke), it was sufficient to confirm his theory. A thick sequence of volcanic rocks, with a basin-like structure, covered an area of about 400 km², and was surrounded by a near-circular ring fracture, partly dyke-filled, with a diameter of 27 km.

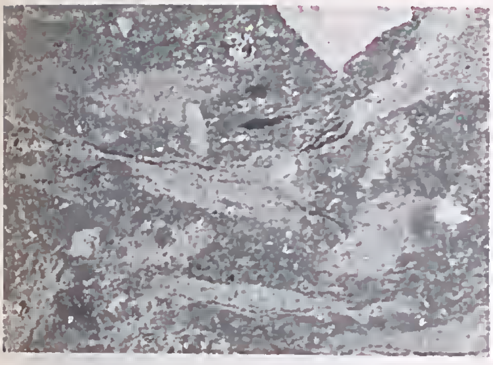
Hills also recognised the Acheron Cauldron to the south, which, together with the Cerberean and a belt of intrusive rocks to the west (the Black Range) formed the Marysville Igneous Complex. He also pointed out that the Marysville Complex was not the only cauldron subsidence in the region. Closely related complexes such as the Violet Town Volcanics were also bounded by near vertical fractures, although these tended to be polygonal, rather than arcuate or elliptical.

The monograph on the Marysville Igneous Complex, which Hills was preparing, has not been published. However, it was made available to D. E. Thomas, who quoted from the manuscript when preparing his 1947 report on the geology of the Eildon Dam site. M. Valiullah, a student at Melbourne University in the early 1960s, also had access to the monograph when undertaking a chemical and mineralogical study of the Central Victorian complexes (Valiullah 1964).

The 1960s saw the widespread application of K-Ar dating to stratigraphic problems in southeastern Australia. The Taggerty-Eildon sequence was ideal and, for a time, the Devonian-Carboniferous boundary was very closely identified with the uppermost rhyodacite in the Cerberean Cauldron (Evernden & Richards 1962, McDougall *et al.* 1966). Hills played a major advisory role in the application and interpretation of the radiometric data.

Thomas' map of the northernmost outcrops of the volcanic rocks in the Cerberean Cauldron was a classic piece of work and the famous Snobs Creek sequence is as significant for the interpretation of the structural history of the complex as the Taggerty fish bed sequence was for the stratigraphic correlation. The Snobs Creek sequence (Table 1) provided the base which enabled groups of honours students from the University of Melbourne to complete, in detail, the mapping begun by Hills some 40 years earlier (Birch *et al.* 1970, Dudley *et al.* 1971). Although he took no part in the field work

Figs 2-9—2, 3, photomicrographs of the base of the Rubicon Rhyolite in the Blue Hills, Taggerty, showing well developed eutaxitic texture. The contorted and flattened pumice fragments were interpreted as flow structure by Hills. 4, microspherulitic structure within flattened pumice fragments in the Rubicon Rhyolite from the Blue Range at Taggerty. These textures are a product of devitrification and vapour phase crystallisation. 5, 6, general texture within the 'fragmental toscanites', now rhyolites and rhyodacites of the Robleys Spur Formation. Note the fragmented phenocrysts in Fig. 5, and the andesite xenolith in Fig. 6. 7, vitroclastic texture (i.e. of flattened shards derived from shattered glass bubbles) well preserved in the Snobs Creek Rhyolite. 8, eutaxitic textures from the base of the Rubicon Rhyolite at Snobs Creek, Eildon. 9, general texture within the Rubicon Rhyolite, higher in the sequence at Snobs Creek. Recrystallization has partially obscured the original eutaxitic textures. Note: Figs. 2-9. Field of view is 3.5×2.3 mm.



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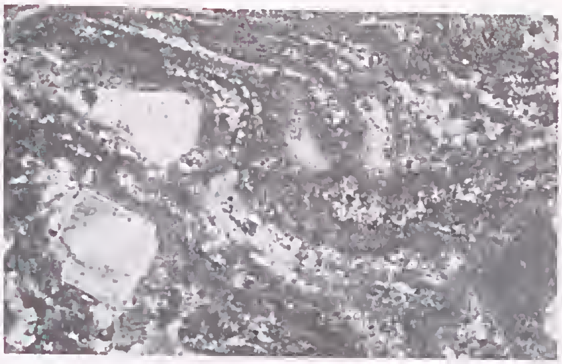

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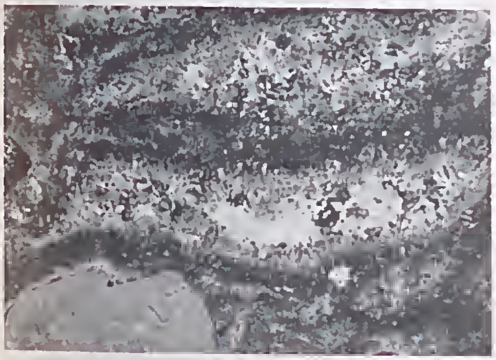

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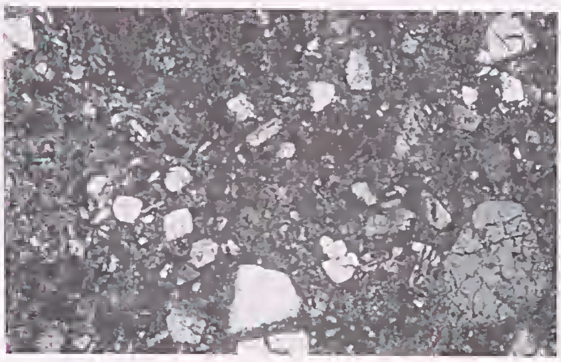

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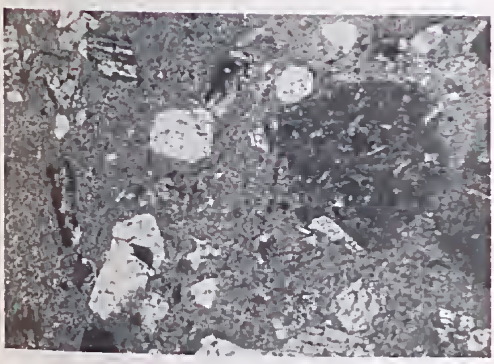

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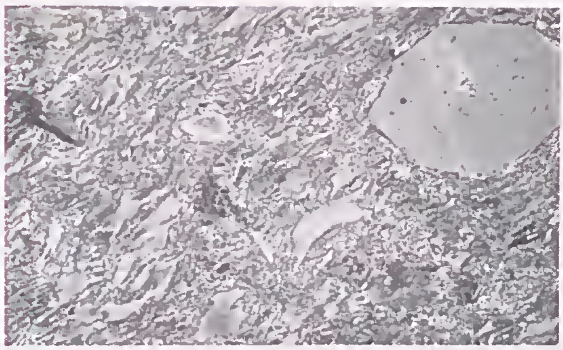

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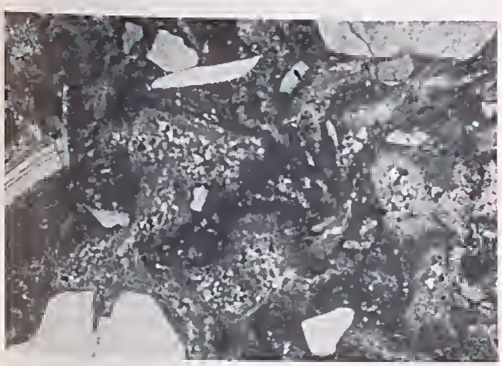

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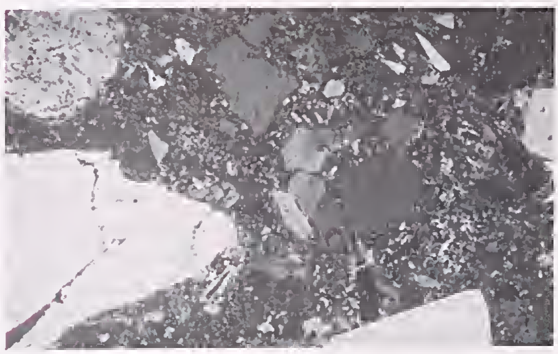

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during the 1970s it was Hills' influence which enabled the projects to be funded.

THE ASH-FLOW CONCEPT

Early Interpretations in Victoria

As already outlined, it was proving to be difficult enough for the early workers on the 'dacites' problem in Central Victoria to confirm the rocks had an extrusive origin without extending the debate to the mechanisms by which silicic volcanic rocks in general were emplaced. It was only when detailed petrographic studies of the 'dacites' were carried out that 'fluidal textures', clearly of volcanic origin, were recognised and described (Gregory 1902, Skeats & Summers 1912). The significance of these 'fluidal textures' naturally escaped even such an astute observer as Skeats, because over fifty years were to elapse before the concept of ash-flow emplacement influenced geological thought in Victoria.

Hills' work on the acid volcanic rocks at Taggerty involved quite detailed petrographic descriptions. In 1929, in Rhyolite α from Taggerty, he noted *'fluxion structure is developed only along the lower edge . . . Through the whole flow—but becoming more numerous towards the base, are xenoliths of sandstone and shale'.*

In describing microscopic features of this rhyolite, Hills noted that *'the groundmass is micro- to cryptocrystalline and always has well developed flow structure, the contorted lines curving around the phenocrysts of quartz and feldspar, which are not arranged linearly* (Figs 2 and 3). *Biotite crystals curve with the flow lines and wrap around the quartz and feldspar. On solidification, the groundmass was evidently a glass . . . Some bands are coarser than others . . . other bands are cryptocrystalline . . . occasional microspherulitic aggregates occur'.* (Fig. 4).

Hills also described the highly fragmented nature of the phenocrysts and the microfluxion structure within the groundmass of Rhyolite β at Taggerty. These features of both rhyolites Hills ascribed to viscous flow and all the acid rocks were considered to be lavas rather than pyroclastics. Similarly the flow planes within the 'Lower' and 'Middle' Dacite units in the Dandenongs Complex were interpreted as bedding within lava flows (Hills 1941).

That Hills began to modify his views is apparent from references to his unpublished manuscript made by Thomas in 1947. Rhyolite β had been renamed the 'fragmental' toscanites (Table 1) in recognition of certain pyroclastic features they exhibited, such as the presence of shattered, but otherwise unaltered phenocrysts (Fig. 5) their well-stratified nature and the occurrence of xenoliths (Fig. 6). Strictly speaking, none of these features is exclusive to pyroclastic rocks, but Hills believed that the fragmental toscanites were erupted as *nuée ardentes*, coinciding with the initiation of the ring fracture. Their emplacement was followed immediately by the extrusion of the great 'nevadite-toscanite-dacite' 'lava' flows (now the Cerberean Volcanics). The suggestion of *nuée ardente* volcanism was apparently as far as Hills was ever to go towards postulating an ash-flow or ignimbritic origin for any of the main acid volcanic units in the Cerberean Cauldron.

Development of the Ash-flow Concept

It is worthwhile setting these local interpretations in an international context. As Chapin and Elston (1979) point out, by 1942 the characteristic field and petrographic features of ash-flow tuffs had been documented worldwide and the relationship of ash-flow eruptions to cauldron collapse structures was well known. Yet the ability to recognise and interpret ash-flow tuffs remained the preserve of a small group of specialists until 1960 and their importance received scant recognition in major texts of the period.

Chapin and Elston advance two reasons for this neglect, namely: 1, the preoccupation amongst igneous petrologists with classification schemes, phase equilibria and differentiation studies; modes of emplacement were unimportant. 2, the great debators on the origin of 'granite' put on their blinkers when it came to large volumes of silicic volcanic rocks; volcanism (i.e. 'basalt') and plutonism (i.e. 'granite') were considered entirely unrelated.

During this period (1942-1960), Hills must have been developing his theories on the significance of acid volcanism in Victoria. Yet there is no published evidence, apart from the case of the 'fragmental toscanites' that Hills embraced the ash-flow theory. As early as 1932, he had acknowledged the problem of emplacing the huge volumes of magma in Victoria (up to 20 000 km² may have been covered to depths of 600-1200 m) by suggesting that fissure eruptions must have been dominant over central-type volcanism. Yet the associated problem, how to emplace widespread, sheet-like, roughly flat-lying deposits, showing continuous and relatively uniform mineralogical zonation, by a process of viscous flow, needed some discussion.

It is intriguing to speculate whether the two factors advanced by Chapin and Elston diverted Hills from taking part in the ash-flow debate. Armed as he was with the detailed stratigraphic, petrographic and structural evidence which he had accumulated in Victoria, he was in a position to profoundly influence the discussion.

Subsequent Interpretation in Victoria

In the early 1960s, the ash-flow theory gained widespread acceptability and respectability as a direct result of the landmark papers by Smith (1960a, 1960b) and by Ross and Smith (1961). These three papers were so thorough in their treatment of the field and petrographic characteristics of ash-flow tuffs that geologists began to fall over each other discovering new examples. Only a very small ripple, however, was felt in Victoria. White (1963) used Ross and Smith's criteria to suggest that the thin basal rhyolite of the Violet Town Volcanics, which he had studied in 1954, was a welded ash-flow. Remnant primary eutaxitic and vitroclastic textures in the chilled base of the overlying highly-recrystallized 'dacite' also pointed to an ash-flow origin for this unit and on this basis. White extended this emplacement mechanism to the main volcanic units in other complexes, including the Snowy River Volcanics.

Brown (1963) disputed White's contention mainly on the basis of thickness/breadth ratios (which he considered, at values up to 1:10, as being too high for ash-flow sheets). Brown did, however, in 1962, reinterpret the Hollands Creek Rhyodacite (a unit underlying the volcanic rocks in the Tolmie Highlands Complex and which he had named in 1961) as an ignimbrite. Although these relatively brief notes generated no further discussion, White and Brown must take credit for undertaking a reinterpretation of their earlier work in the light of prevailing developments in ash-flow theory.

In 1968, M. D. Leggo described 'recrystallized ignimbrites' from the base of the Jemba Rhyolite but did not suggest the entire rhyolitic unit was an ash-flow deposit. The major reinterpretation took place in the early 1970s, when a re-examination of the 'fluxion structure' observed by Hills at the base of the main rhyolite (Rhyolite α, 'Nevadite', Rubicon Rhyolite) in the Cerberean Cauldron revealed it as remnant eutaxitic and vitroclastic textures typical of welded ash-flow tuffs (Birch *et al.* 1970). Recrystallisation, due mainly to the great thickness (and therefore retained heat) of the flow units, had obliterated primary textures from all but the thin basal zone (Birch 1978). All the major rhyolite and rhyodacite units in the sequence, from the Snobs Creek Volcanics upwards, showed characteristic features of welded ash-flows (Figs. 5-9).

Since then, more intensive study of the petrographic features of volcanic rocks in the Strathbogie and Tolmie Highlands Complexes (Clemens 1981, Birch 1978, 1975), the Jemba Rhyolite (Birch 1978) and the Dandenongs Complex (VandenBerg 1971) has demonstrated the universality of the ash-flow emplacement mechanism in Victoria.

Quite sophisticated studies on the major ash-flow deposits in the U.S.A. and New Zealand have since extended the knowledge of the emplacement mechanisms and the resulting textural, mineralogical and chemical variations (e.g. Sparks 1976, Sparks & Walker 1977, Sparks & Wilson 1976, Sparks *et al.* 1973, Christiansen 1979, Hildreth 1979, Wright *et al.* 1981). In many cases however, non or poorly welded ash-flow units were the objects of investigation and the application of the results to the densely welded Victorian examples is not necessarily practical nor valid.

General Pattern of Ash-flow and Cauldron Subsidence Relationships

The relationship between large collapse structures and silicic volcanism was first demonstrated by Williams (1941). Although this now has universal acceptance, there is still some disagreement over terminology relating to the structures themselves. Williams established the term 'caldera' for large, approximately circular volcanic depressions produced by 'engulfment'. The term 'cauldron' has been used for a wide range of structures and Smith and Bailey (1968) considered it appropriate for all volcanic structures regardless of shape, size or depth of erosion. While 'caldera' is now widely acceptable in the U.S.A. and elsewhere, 'cauldron' is used more often in Australia, possibly due to the influence of Hills' 1959 discussion paper. However, there is no clear distinction between complexes described in the literature as calderas or cauldrons, and fundamentally the same mechanism probably gives rise to all such structures. The term 'cauldron subsidence', when applied to the central Victorian complexes, will be persevered in this paper, on the understanding that it is broadly synonymous with 'caldera'.

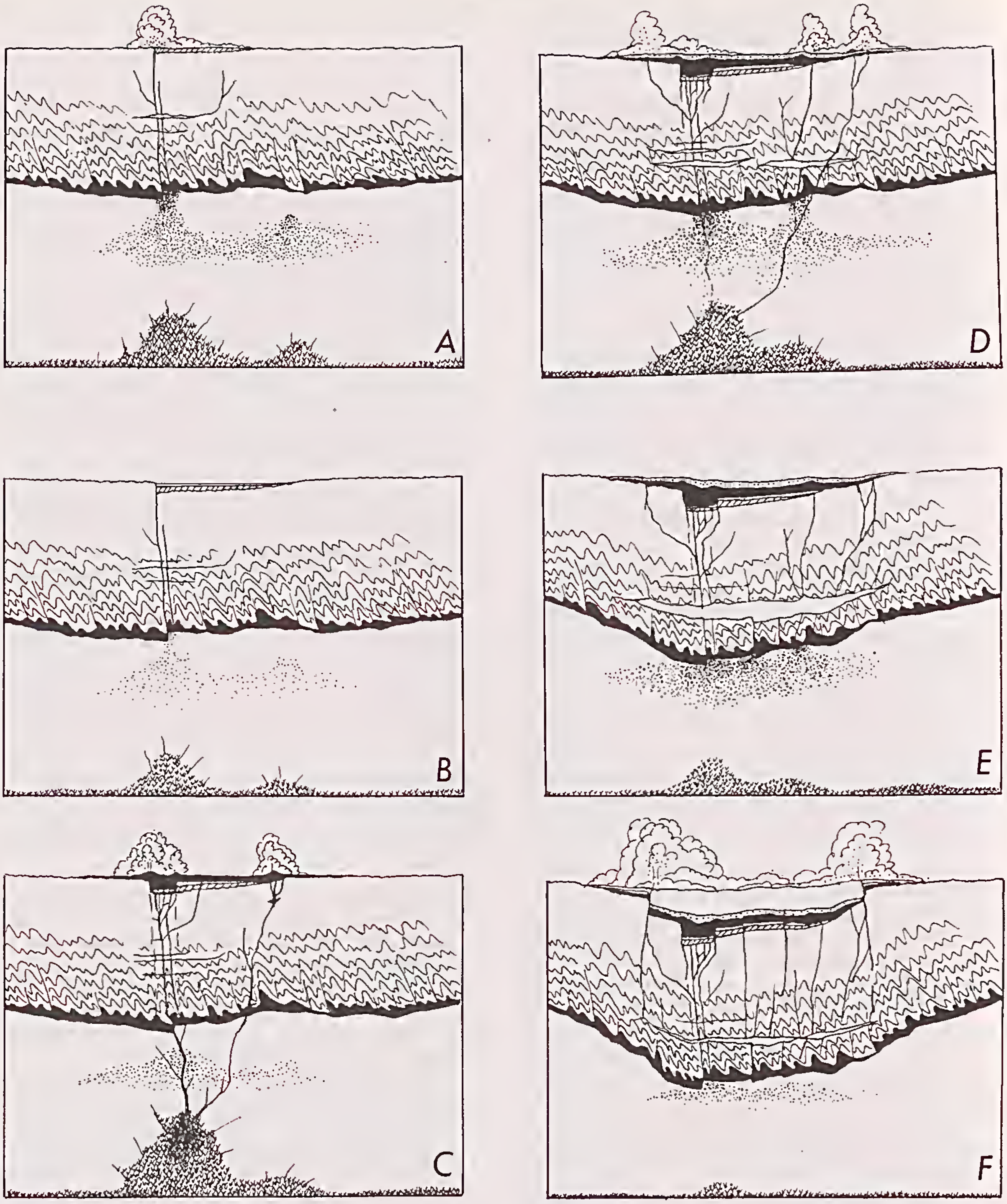
In framing a model, account must be taken of a diverse set of parameters. Scale is a useful initial discriminant. Ash-flow volumes of the order of 100 to 1000 km³ are characteristic of large epicontinental ring structures, and of the silicic volcanic eruptions associated with the large plutons of the circum-Pacific batholith complexes (Smith 1979). The central Victorian province fits into this latter category.

From the discussion papers of Smith (1979) and Christiansen (1979) a number of broad relationships may be defined, namely: 1, there is a positive correlation between the area of subsidence and the ash-flow eruption volume. 2, most large subsidence complexes show some degree of periodicity, with cyclic episodes of ash-flow eruption, occasionally with more basic lavas associated. A time scale of thousands to hundreds of thousands of years may be involved in a single cycle. 3, large ash-flow sheets show some degree of chemical and mineralogical variation inherited from the magma chamber. In general, they range from rhyolitic to dacitic or andesitic, reflecting a magma chamber becoming increasingly mafic with depth. This fractionation may have a number of origins. 4, most large-volume ash-flow sheets show an increase in phenocryst content upward in the sheet. The upper zone of phenocryst-poor magma within a crustal chamber is a low-temperature layer rich in volatile material; eruption inverts this zonation. 5, in large-volume silicic magmas, a maximum viscosity range above which ash-flows do not form appears to be in the region of 50% phenocryst content. 6, ash-flow sheets may represent both volatile oversaturated and volatile undersaturated magmas. In either case they represent the partial catastrophic evacuation of a shallow magma chamber from the top downwards.

The Development of the Cerberean Cauldron Model

Hills' 1959 paper was a major contribution to the discussion on the mechanisms of 'cauldron subsidence'. There is little doubt that the Victorian region, and particularly the Cerberean Complex, is a key area in developing an understanding of the fundamental processes involved.

Based on the mapping of the Taggerty, Marysville-Cumberland and Eildon sequences within the Cerberean Complex, Thomas (1947), with the assistance of Hills, established the first model. It invoked progressive basining and continuous volcanism, with acid lavas and



pyroclastics interbedded with lacustrine sediments, prior to extrusion of widespread and generally overlapping basic lavas. In areas within the new, more developed basin, substantial lake deposits were ultimately represented by the Taggerty Fish Beds in the southwest, but marked by only thin tuffs in the Eildon area.

They were followed by extensive *nuée ardente* eruptions emplacing the 'fragmental' toscanite series. This marked the formation of the ring fracture, the obliteration of lakes within the ring and the beginning of subsidence into the underlying magma chamber. The rise of the main 'nevadite-dacite' series along the ring fracture

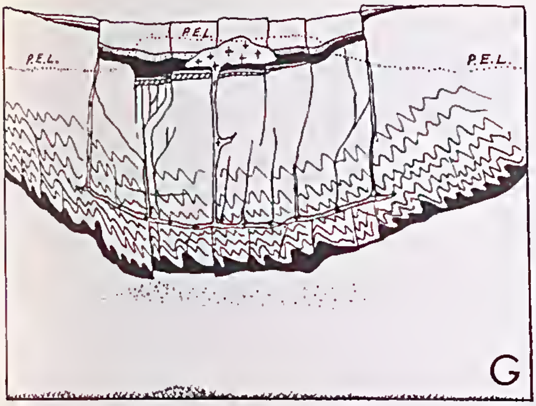


Fig. 10—Series of diagrams showing the development of the Cerberean Cauldron, based on an original model of Birch *et al.* (1970). The current model assumes the presence of a lower crustal sialic layer beneath Cambrian 'greenstones' (shown in black) and the folded Palaeozoic fill of the Melbourne Trough (see magma origin section for discussion of crustal structure). Partial melting is attributed to basic diapirism into this lower crustal layer. The diagrams are approximately to scale, except for the expanded thicknesses of the individual volcanic units. Fold styles and faults are diagrammatic only.
a, eruption of ash-flows forming the Snobs Creek Volcanics following partial melting of the lower crust. Some subsidence in the region, with movement along the Snobs Creek Fault. b, cessation of volcanism and the formation of lakes in the basin, with deposition of the Blue Range Formation. c, a renewal of volcanic activity with the widespread eruption of the andesites of the Torbreck Range Formation. These may have an upper mantle origin. A caldera, largely filled with andesites, developed on the Snobs Creek Fault. d, a return to acid ignimbritic volcanism with some associated andesitic lavas, forming the Robleys Spur Formation. Extensive partial melting in the lower crust, with accumulation of magma at higher levels. More marked regional subsidence commencing. e, continuous partial melting leading to a large differentiated magma chamber. Regional subsidence continuing. f, volatile saturation attained in upper levels of magma chamber leads to explosion generating radial and ring fractures. Crustal blocks subside into magma chamber accompanied by large scale ash-flow eruption of the Rubicon Rhyolite and Lake Mountain Rhyodacite filling the 'cauldron'. g, upward migration of remaining magma to form ring and radial dykes and high level granodioritic intrusions into the base of the volcanic pile. Region stabilizes and erosion commences.
(P.E.L. = Present erosion level)

then followed. Ultimately, the subsidence along the steeply outward-dipping ring fracture was 600-900 m, where measurable close to the fracture, but basining, evidenced by decreasing inward dips of the volcanic units up-sequence, indicated that a likely subsidence of 1600 m occurred at the centre of the block.

The mapping of the entire complex in the 1970s resulted in a number of modifications to this initial model, arising mainly from the discovery of a set of radial faults and the conclusion that all the acid volcanic units were ash-flows (Birch *et al.* 1970, 1978).

The essential points of the current model are outlined below and shown diagrammatically in Fig. 10.

1. The cauldron is a cylindrical block, which has subsided along an integrated pattern of circular and radial faults which essentially operated contemporaneously. Greater subsidence at the centre of the block has led to basining of the volcanic pile.

2. The earliest known fault associated with the cauldron structure is Snobs Creek Fault, which was operative during the emplacement of the first ash-flows (Snobs Creek Volcanics) (Fig. 10A). It was parallel to regional basement trends and was hinged, with opposite vertical displacements at either end.

3. An inner ring fracture, partially dyke filled and exposed on the northeastern margin of the cauldron, may represent an early-formed caldera centred on Snobs Creek Fault (Fig. 10C).

4. Source vents for the earliest ash-flows were probably associated with Snobs Creek Fault. The suspected early caldera may have been a vent for the basic-intermediate lavas of the Torbreck Range Formation. There is no direct evidence for the ring dyke being a source vent for the Robleys Spur Volcanics (incorporating the 'fragmental' toscanites) (Fig. 10C). Other feeders, either central vents or fissures, have probably been covered by the later ash-flows (Clarke *et al.* 1970). The Cerberean Volcanics were undoubtedly erupted from the outer ring fracture.

5. Basining and ring fracture components make up the overall subsidence. Early basining is indicated by decreasing inward dip of the volcanic units up sequence, as suggested by Thomas (1947), and the deposition of the lacustrine Blue Range Formation (Taggerty fish beds) (Fig. 10B). Thus, the region was probably under tension before failure took place along the ring fracture. Major subsidence along the ring fracture postdates the Rubicon Rhyolite, but subsidence probably occurred progressively throughout emplacement of the Cerberean Volcanics (Fig. 10F).

6. The evidence from the well-established steep outward dip of the ring-dyke is inconclusive for the establishment of a model for the origin of the fracture pattern. However, the overall ring and radial fracture pattern and the stretching of the foundered block suggest that the roof of the magma chamber behaved as a circular plate. A 'point' explosion at depth appears to best explain the fracture pattern, possibly as the magma attained volatile saturation in its upper region (Fig. 10F). Violent ash-flow eruptions then proceeded via the fractures and enabled wedge-shaped crustal fragments to subside, differentially, into the magma chamber as support was withdrawn.

7. High level magmas, in two main phases, intruded the base of the volcanic pile to the south (Fig. 10G). No resurgent volcanism is observed.

Modelling of the spacing geometry of volcanic and intrusive centres in the southern portion of the Lachlan fold belt by Rickard and Ward (1981) suggested the presence of an upper 'brittle' crustal layer averaging about 10 km thick. This layer modified the manner in which magmas derived from deeper levels in the crust were emplaced. Direct evidence for the existence of such a layer may be seen in the foundered roof block of the Cerberean Cauldron, which behaved like a circular plate with a probable thickness less than half its diameter of 27 km. The above model is not entirely applicable to the other major subsidence structures in central Victoria, in that none show the regularity, cyclic volcanism or variable early sequences to the degree exhibited by the Cerberean, which is probably the most regular and best preserved Palaeozoic ash-flow/subsidence complex known. Taken as a group, however, the features shown by the central Victorian complexes are similar to those of Mesozoic and younger calc-alkaline complexes in the circum-Pacific belt, particularly in Chile, Nevada, Alaska, and New Zealand. Perhaps the most noticeable differences, neglecting any mineralogical or chemical distinctions, are the absence of extensive non- or poorly welded units, the scarcity of identifiable ash-fall beds, the unusually large thicknesses and the high phenocryst contents within the central Victorian sequences. The textural variations associated with base or pyroclastic surge (Wohletz & Sheridan 1979) are lacking in the major units, which are all densely welded and show relatively uniform vertical chemical and mineralogical variations (Birch 1978). Emplacement temperatures were therefore high, probably greater than 500°C (Clemens 1981), and there is no evidence for gravitational column collapse (Sparks & Wilson 1976) as a driving mechanism for the pyroclastic flows. Instead, the kinetic energy of the ash-flows was probably derived from the subsidence of the crustal blocks into the magma body. It is possible, however, that large volumes of ash-fall and non- or poorly-welded pyroclastic deposits originally blanketed much of the area between individual complexes, and have since been removed by erosion. Most of the complexes owe their preservation to downfaulting as much as to differential erosion rates.

OTHER VICTORIAN COMPLEXES

Comparison of the central Victorian complexes with major belts of acid volcanic rocks in western and eastern Victoria reveals major differences in age, structural control, mineralogical characteristics and degree of preservation. Most of the major belts outside the central region have not been investigated in detail and further work is desirable. From west to east, the main belts are as follows (See Fig. 1).

Rocklands (& Wickliffe) Rhyolite: This is a generally poorly exposed belt of rhyolitic rocks and pyroclastics, of unknown age, underlying the Siluro-Devonian sediments of the Grampians Group and overlying Cambro-Ordovician basement. The rhyolites average only about 2% phenocrysts (quartz and K feldspar) and are often characterised by a laminated appearance (Dennant 1893), with fine-scale continuous banding in alternating sodic and potassic layers (Hallenstein 1971). These are frequently highly contorted (Fig. 11). More massive porphyritic varieties outcrop in the Hamilton area (e.g. in Grange Burn). The rhyolites are essentially flat-lying but their mode of emplacement is uncertain,

Fig. 11 — Hand specimen showing contorted flow banding (?) in the Rocklands Rhyolite (NMV E4511). Specimen is 14 cm long.

although they may well be thick lava flows or coalescing domes (I. A. Nicholls pers. comm.). No collapse structures or vents are evident. Limited chemical data indicate an S-type character for the magmas.

Mt. Macedon Complex: The smallest of the Late Devonian central Victorian complexes, measuring about 8 by 8 km, it consists of a single rhyodacite unit at least 300 m thick which is mineralogically similar to the uppermost units in the Acheron Cauldron and Dandenongs Complex. A small granodiorite body has intruded the rhyodacite on the eastern side. Since no evidence for a ring fracture has been discovered, the rhyodacite probably represents the filling of a volcanic depression by ash-flow eruptions. No detailed investigation of textures within the rhyodacite has been undertaken since the descriptions by Gregory (1902) and Skeats and Summers (1912). However, a photomicrograph of a 'cryptocrystalline' 'hypersthene andesite' clearly shows eutaxitic textures (Skeats & Summers 1912, Fig. 2).

Strathbogie Complex (Violet Town Volcanics): The Violet Town Volcanics outcrops over 240 km² in northern Victoria, occupying an elliptical downwarp, and forming the northern component of the Late Devonian Strathbogie Complex (White 1954, Hills 1959). The simplified sequence within the volcanics consists of three ash-flow tuff units, beginning with a thin rhyolite (Fig. 12) grading to a rhyodacite. This is overlain by a thicker (100 m) rhyolite-rhyodacite unit and the uppermost unit is a uniform crystal-rich rhyodacite up to 200 m thick (Birch *et al.* 1977) almost identical to the Lake Mountain Rhyodacite in the Cerberean Cauldron. The rocks are extensively recrystallised, but sufficient primary textures are preserved to enable them to be identified as ash-flows (White 1963, Clemens 1981). The general structure of the Violet Town volcanics is sheet-like with a slight northward tilt but a marked upturn along the intrusive southern contact with the granite of the Strathbogie Batholith (Phillips *et al.* 1981).

Dandenong Ranges Complex: The volcanic rocks and

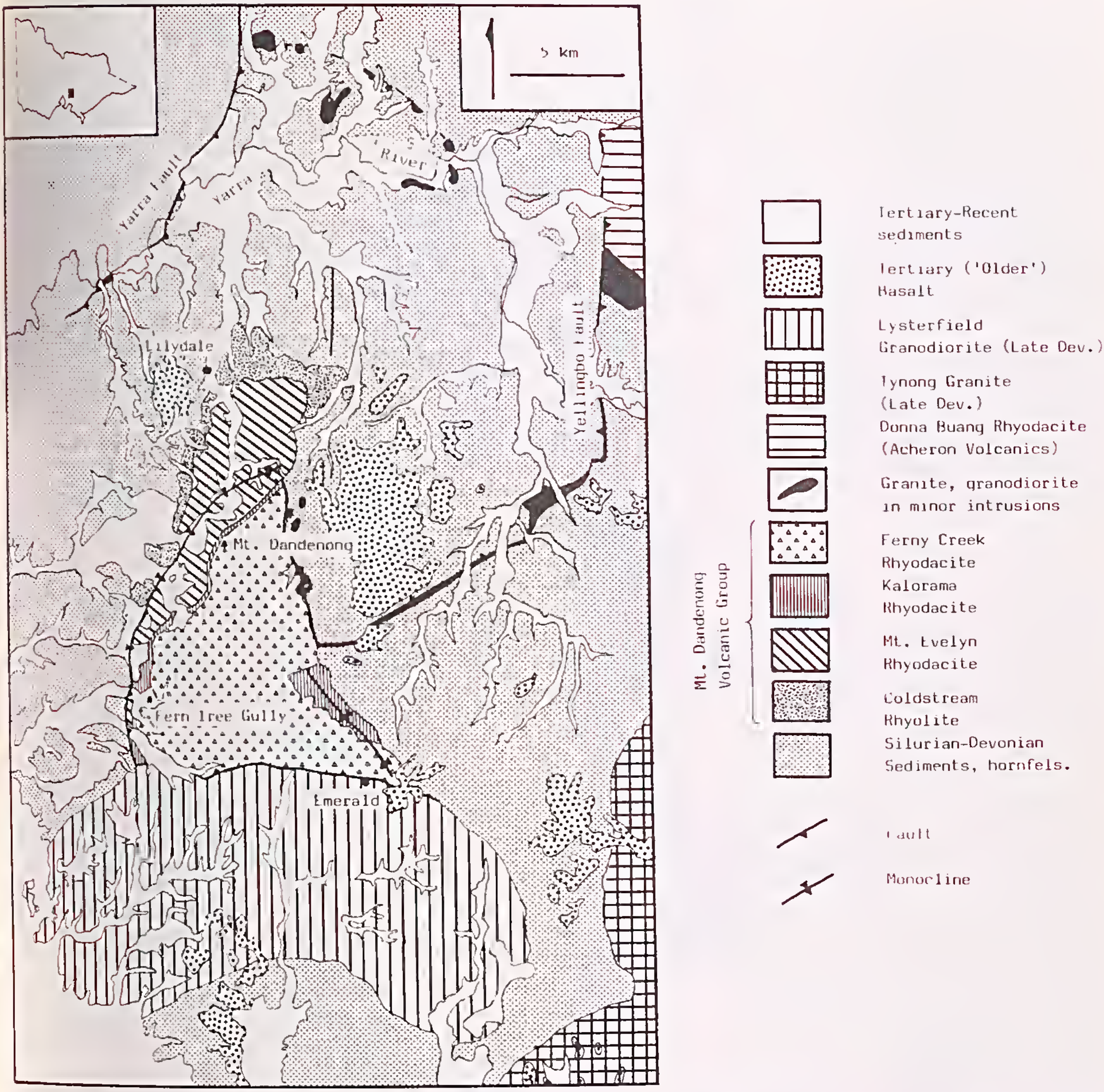


Fig. 13—Geological map of the Dandenongs Igneous Complex.

the granodiorite in this complex occupy a roughly triangular trough-like structure, 330 km² in area, which appears to be a simple syncline in the north, but is complicated by cross-cutting faults and monoclinal warps in the south (Fig. 13). Near vertical easterly dips occur in the volcanic rocks on the western margin (Hills, 1941), indicating severe post-emplacement subsidence. Early mineral analyses from the 'dacites' were undertaken by Richards (1909). The sequence was first subdivided by Morris (1914), described (as lavas) in detail by Edwards (1956) and revised by VandenBurg (1971). With the possible exception of the lowermost flow in the basal Coldstream 'Rhyolite' the volcanic rocks are thought to be welded ash-flows (McLaughlin 1976). The Coldstream Rhyolite is overlain by a series of rhyolitic and rhyodacitic ash-flows forming the Mt Evelyn Rhyodacite. The main collapse phase is represented by two uniform rhyodacite units, the Ferny Creek Rhyodacite overlying the Kalorama Rhyodacite. There are some similarities between the general sequence in the Dandenongs Complex and the upper part of the sequence in the Acheron Cauldron, 16 km to the north. In particular, the Donna Buang Rhyodacite and Ferny Creek Rhyodacite appear equivalent. The southern margin of the volcanics is a fault contact with the Lysterfield granodiorite, along which the rhyodacites

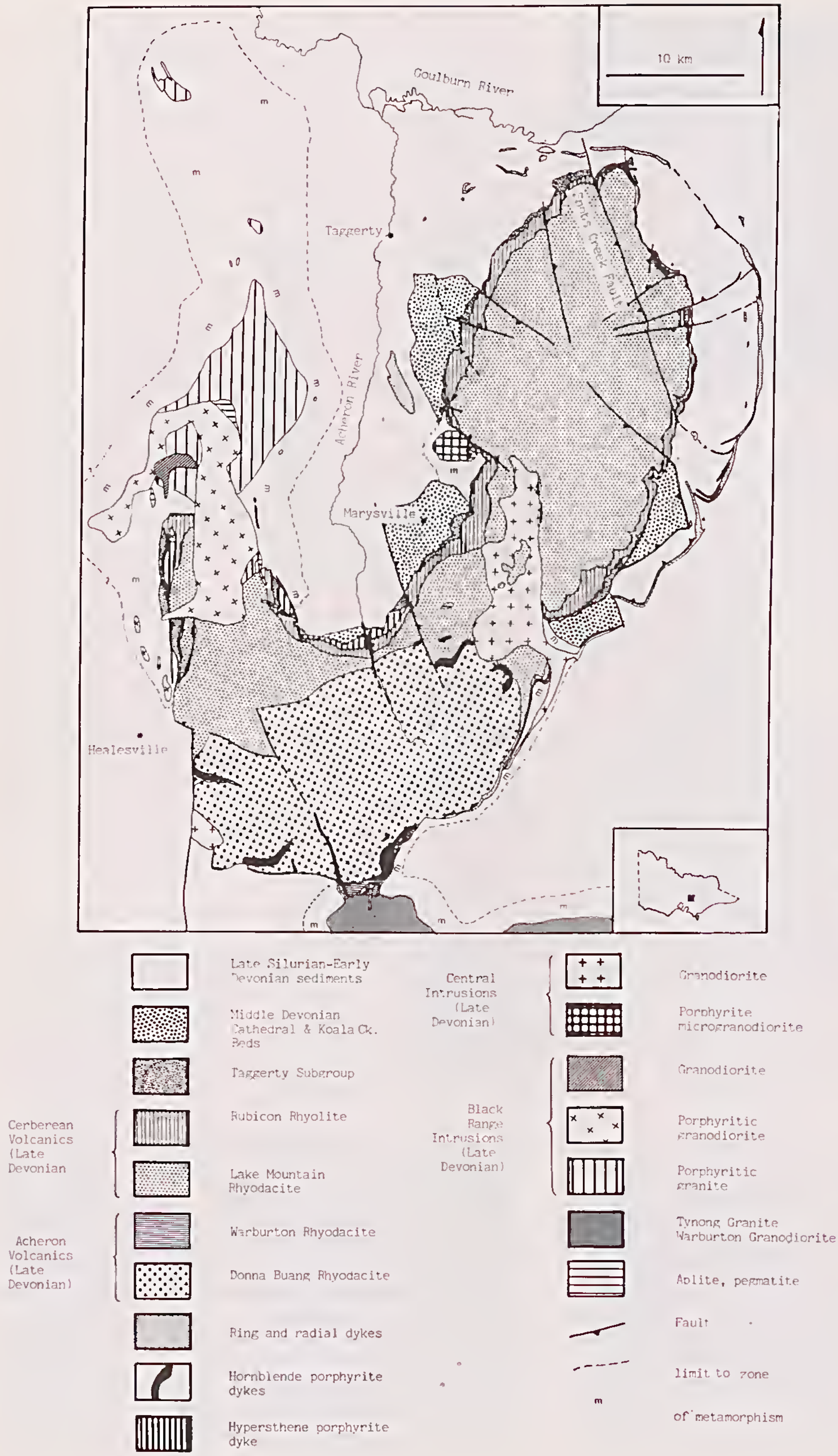


Fig. 14 – Geological map of the Marysville Igneous Complex (after Dudley *et al.* 1971, Birch *et al.* 1970).

have become schistose (Skeats, 1910). There is some evidence for an arcuate fracture, with a few pods of quartz porphyry, around the northern margin of the complex and possibly continuous with the main Yellingbo Fault cutting the volcanics (Fig. 13).

Marysville Igneous Complex (Cerberean and Acheron Cauldron): The Cerberean Cauldron (Fig. 14) has been discussed in sufficient detail above. The Acheron complex to the south was considered by Hills (1959) to be a hinged flap, with volcanics thickening to the south (Fig. 14). All the volcanic, chiefly rhyodacitic, units are welded ash-flows (Dudley *et al.* 1971) and a number of units are common to both (Table 1). The Acheron Cauldron subsidence probably occurred after the main Cerberean subsidence, as the youngest unit (the Donna Buang Rhyodacite) is absent from the latter. The style of subsidence is also different, with the foundered block of the Acheron delineated by generally straight fractures, juxtaposing volcanics with basement sediments, and suggesting some post-depositional subsidence.

The main intrusive phase includes a complex belt in the Black Range, to the northeast (Howard 1972), and an extensive granodiorite intruding the volcanic sequence in the junction region between the two cauldrons (Birch *et al.* 1978, Bini 1982) (Fig. 14).

Tolmie Highlands Complex: This Complex straddles the Mt. Wellington Axis, the eastern boundary of the Central Victorian Trough. Unlike other multi-unit complexes it consists almost entirely of rhyolitic rocks. Although Brown (1961) included the older Holland's Creek Rhyodacite (a welded ash-flow) and associated conglomerates and clastic sediments within the complex, these occupy an older depositional basin and are separated by a period of erosion and block faulting from the younger volcanic episodes (Clemens 1981, Gaul 1982). As mapped by Brown (1961), the volcanics occupy a basin, fault-bounded on its northeast, east and south margins, with a major northwest-southeast fault separating two sub-basins. More recent mapping (Gaul 1982) has suggested subsidence on a more rectilinear horst and graben-like basis, some of it post-depositional (Fig. 15). Rhyolitic rocks occur as two main thick ash-flow units, the Ryans Creek Rhyolite (Birch 1975, 1978) (Fig. 16) and the Toombullup 'Rhyodacite' (which is rhyolitic, at least in the lower portions). To the south, the contact between the two is sharp and may be marked by an ash-fall layer (Clemens 1981). In the north and northeast, the Ryans Creek Rhyolite fingers out, forming flat-lying hill cappings, and may show gradational contacts with the overlying Toombullup 'Rhyodacite'. A separate wedge-shaped rhyolitic unit (the Molyullah Rhyolite) overlies the Toombullup 'Rhyodacite' in a fault-bounded basin in the north (Gaul 1982, Birch *et al.* 1977). Isolated pods of intrusive rocks occur near the margins of the complex, but there is no semi-continuous ring dyke and no evidence for a ring fracture (Gaul 1982). A number of post-volcanic faults complicate the stratigraphy. The Barjarg Granite, the equivalent of the Strathbogie Batholith (Phillips *et al.* 1981), intrudes the volcanics in the southwest.

Wellington Rhyolites: A widespread, relatively uniform series of rhyolitic rocks occurs conformably within the Late Devonian-Early Carboniferous 'red-bed' sequences (Avon River Group) in the Macalister and Avon Synclinoria in east central Victoria (Neilson 1964). The rhyolites represent a single period of eruption and form a sheet-like unit up to 600 m thick. The outcrop area measures about 100×45 km, encompassing the two main basins. Weakly alkaline basalt flow sequences up to 400 m thick are interbedded with the sedimentary rocks both above and below the Wellington Rhyolite (Sutton 1978), which also contains a few thin basalt flows (Neilson 1976). No source vents for either rhyolite or basalt have been described.

Although a wide variety of textural terms have been used (e.g. Neilson 1976) the main variant is a pale, phenocryst-poor aphanitic rhyolite showing 'flow textures'. Early petrographic descriptions of 'fluidal' and pyroclastic textures by Skeats (1909) and Thiele (1908) are suggestive of eutaxitic textures. More recent studies (Sutton 1978, Buckley 1982) indicate that the rhyolites are variably welded and were emplaced by large scale ash-flows (Figs 17-19).

Jemba Rhyolite: Hills (1959) recognised the Jemba Rhyolite as a cauldron subsidence region and it is the only occurrence in eastern Victoria where there is clear evidence for both cauldron subsidence and ash-flow emplacement (Fig. 20). It is also the oldest complex of this type in Victoria, being dated at 400 Ma (Richards & Singleton 1981; corrected data of Brooks & Leggo 1972).

The Jemba Rhyolite forms a prominent plateau of 65 km² and elliptical in outline. It consists entirely of rhyolitic rocks, the sequence being up to 650 m thick. A welded crystal-rich rhyolitic ash flow forms a single cooling unit over 400 m thick. Although primary eutaxitic and vitroclastic textures are preserved at the base of this unit—Leggo (1968) first described recrystallised 'ignimbrites' from the basal zones—these are rapidly obliterated by recrystallisation upwards in the unit (Birch 1975, 1978; Figs 21 & 22). Thin rhyolitic ash-fall and rhyolite flow units outcrop at the base of the sequence in the north (Oates & Price 1983). Chemical and mineralogical trends within the main mass have been discussed by Birch (1978), Oates (1980), and Oates and Price (1983). An arcuate ring fracture within the Late Ordovician metasedimentary basement completely encloses the rhyolite and is marked by about ten small granitic intrusions (Fig. 20).

Mitta Mitta Volcanics: The volcanic rocks in the Mitta Mitta graben, north of Benambra, occur in three separate belts (I. A. Nicholls pers. comm.), apparently separated by faults and extending for about 45 km. In the southernmost belt, phenocryst-poor acid volcanics outcrop as steep cliffs in the valley of the Mitta Mitta River (Bolger 1982). Recrystallisation is extensive and there is little evidence for emplacement mechanisms. The volcanics may be lavas (Cook 1978). In the central belt (Larsen Creek and the Dart River), a wide range of mass-flow breccias, ash-flow tuffs, minor lavas and in-

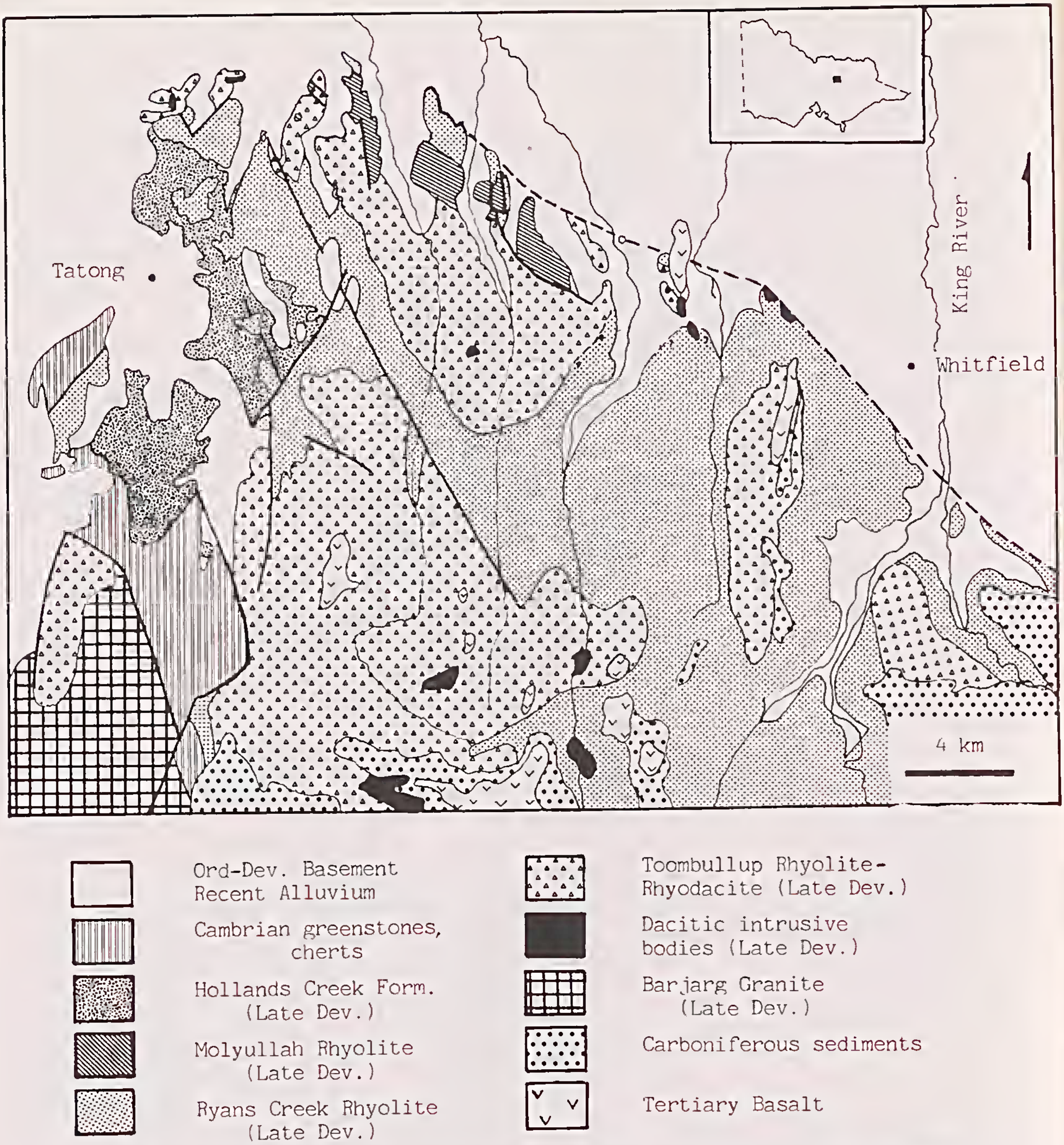


Fig. 15—Geological map of the northern portion of the Tolmie Highlands Complex (after Gaul 1982, Brown 1961).

trusive rocks are exposed. Well-developed eutaxitic textures are preserved in dacitic-rhyodacitic ash-flows (Bolger 1979, I. A. Nicholls pers. comm.). In the northern belt, near Mt. Benambra, a thick sequence of crystal-rich rhyolitic ash-flow tuffs occurs. The rocks within the southern belt of the Mitta Mitta Volcanics are similar to those in the Thorkidaan Volcanics, and both are probably Middle-Late Silurian (VandenBerg *et al.* 1979). The central and northern belts may be Early Devonian (P. Bolger pers. comm., I. A. Nicholls pers. comm.).

Thorkidaan Volcanics: These form a broad, northeast-southwest trending belt, 30×10 km, in the Limestone Creek area in northeastern Victoria. They consist of a thick sequence of rhyolites with minor rhyodacite, and ash-fall and possibly fluviatile tuffs. The volcanics are variable in appearance and phenocryst size and abundance. Despite the extensive recrystallisation, chloritisation and sericitisation affecting the groundmass, sufficient textural evidence is preserved to indicate an ash-flow origin for many of the rocks (VandenBerg *et al.* 1979) (Fig. 23). However, autobrecciated and flow-banded rhyolitic lavas are also present, particularly in the Tambo Valley, near Bindi (Lew 1979). The Thorkidaan Volcanics are tentatively placed in the Middle to Late Silurian. The Silurian sequence of which they are a part is uncomformably overlain by the main north-south belt of Snowy River Volcanics.

Snowy River Volcanics: This is the most voluminous series of acid volcanic rocks in the state, with the main outcrop being an irregular north-south trending belt, 110 km long and up to 50 km wide, extending from Limestone Creek and Suggan Buggan to Nowa Nowa, in eastern Victoria. They are stratigraphically dated as Early Devonian and the major rock types are porphyritic rhyodacite and dacite, with minor rhyolites, andesites, basalts and intercalated sediments (Ringwood 1955, Tattam 1976). The rhyolites and rhyodacites frequently show eutaxitic textures and much of the formation represents extensive ash-flow sheets preserved, not by cauldron subsidence, but by contemporaneous and subsequent rectilinear faulting (Talent 1965). A wide range of debris flows, lahars, lag breccias and lacustrine sediments is also present (Orth 1982). Despite widespread alteration, including albitisation, silicification and chloritisation, textures in the Snowy River Volcanics are much better preserved than in the Thorkidaan Volcanics.

Other Occurrences: Minor occurrences of mainly Late Devonian acid volcanics interbedded within sedimentary sequences are known outside the main belts. For example, rhyolite and rhyodacite ash-flow units occur at Mt. Timbertop, Mt. Cobbler, The Bluff-Bindaree and in the South Blue Range in the northern region of the Mt. Howitt Province. Garnet-bearing rhyodacite units have been mapped in the Bendock area, further east (P. Bolger pers. comm.). Occasional pebbles of acid volcanic rocks, sometimes with eutaxitic textures (Fig. 24) occur in the Permian glacial deposits in central Victoria. A small inlier of hornblende and biotite-bearing dacite and rhyodacite occurs within granodiorite at Dromana on the Mornington Peninsula (Baker 1938).

PETROGENETIC IMPLICATIONS

Continuous generation of acid magmas, and their emplacement by ash-flow, ash-fall and lava-flow (as well as intrusive) mechanisms occurred in the Victorian region from the Middle-Late Silurian to the Late Devonian. There are, however, significant differences between the so-called central Victorian complexes (Macedon, Marysville, Strathbogie, Tolmie and Dandenongs) and the western and eastern belts (Rocklands, Wellington, Jemba, Mitta Mitta, Thorkidaan, Snowy River), particularly with respect to age, periodicity, structural style and mineralogy.

AGE: The central Victorian complexes are Late Devonian, while the western and eastern belts span at least the period Late Silurian to Early Devonian.

PERIODICITY: There is an apparent absence of cyclic activity in the western and eastern occurrences, although not all the central complexes show periodicity to the same degree.

STRUCTURAL STYLE: The central Victorian complexes are associated with roughly equidimensional collapse structures, bounded either by a clearly marked ring fracture, by one or more fault systems which may have been differentially active, or by monoclinal warping. Only the Jemba Rhyolite of the eastern occurrences is clearly bounded by a ring fracture. The remainder appear to occupy roughly linear graben-like structures.

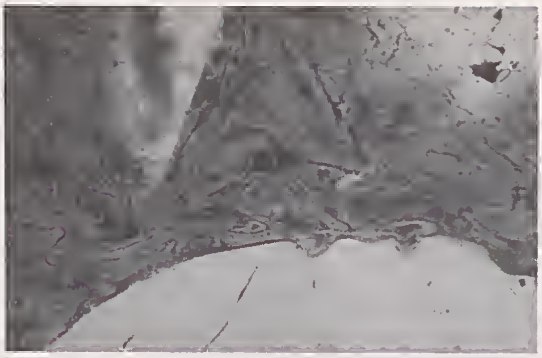
MINERALOGY: The rock types in the central complexes are characterised by iron-rich assemblages including biotite, garnet, cordierite, orthopyroxene and, less commonly, fayalite. The eastern and western sequences, are generally less iron-rich and aluminous and tend to be monotonous in their phenocryst mineralogy which often involves quartz, two feldspars and small, varying amounts of biotite. However, dacitic ash-flows within the Snowy River and Mitta Mitta volcanics may contain phenocrysts of hypersthene, augite and hornblende (I. A. Nicholls, pers. comm.).

CHEMISTRY AND MINERALOGY

The general chemical characteristics of the central Victorian volcanic rocks are now well established. They can be summarised as: high silica contents (most analyses show more than 65% SiO_2), high aluminium and low calcium contents (reflected in normative corundum and hypersthene), high Fe/Mg and generally high K_2O/Na_2O ratios. The chemical (and mineralogical) features show clear affinities with S-type granitic liquids (Chappell & White 1974); i.e. all rhyolitic rocks (with >72% SiO_2) from the major central Victorian complexes have $Na_2O<3.2\%$ for $K_2O \geq 5\%$, Mol. $Al_2O_3/(CaO+Na_2O+K_2O)>1.1$ and CIPW normative corundum >1%. I-type magmas (Chappell & White 1974) appear to be absent from the central Victorian belt.

Chemical variation is most marked in the rhyolitic rock types (72 to 78% SiO_2), which show increasing K_2O, CaO, Ba and Sr and decreasing Rb and Na with increasing sample height within a particular stratigraphic sequence (Birch 1975). The rhyodacitic units tend to be more uniform. The Donna Buang Rhyodacite and its probably equivalent, Ferny Creek Rhyodacite, are the most basic (av. 64% SiO_2) and limited data (Skeats & Summers, 1912) suggest that the Macedon Rhyodacite is similar. The Lake Mountain Rhyodacite and the upper Rhyodacite unit in the Violet Town Volcanics are more acidic (av. 69% SiO_2). The misnamed Toombullup Rhyodacite is actually a rhyolite with 70-72% SiO_2.

The chemistry of the western and eastern acid volcanic belts is not well known. Limited data indicate that the Rocklands Rhyolite is S-type (Hallenstein,



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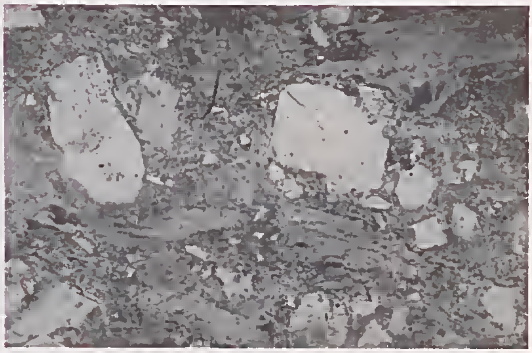

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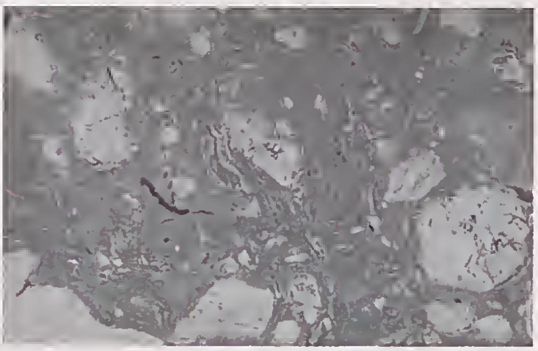

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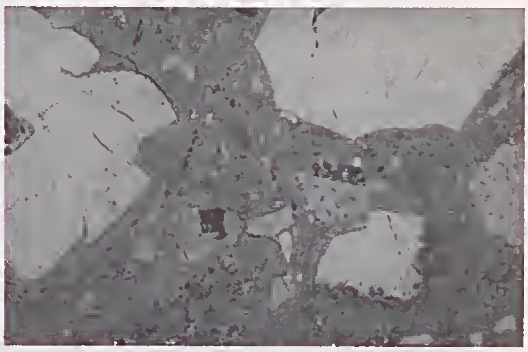

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1971). The Jemba Rhyolite is weakly peraluminous and cannot be classed as either S or I type (Oates & Price 1983). The only published chemical data on the other eastern belts are a few analyses of intermediate rocks of the Snowy River Volcanics near Buchan (Cochrane & Sampson 1950). However, unpublished petrographical and analytical studies on the Mitta Mitta Volcanics (central belt) and the Snowy River Volcanics (Porritt 1976, Sielecki 1980) indicate I-type mineralogical characteristics (hornblende and clinopyroxene phenocrypts in dacites and rhyodacites) with transitional geochemical features (weakly diopside normative to weakly corundum normative) (I. A. Nicholls, pers. comm.).

The rocks in the central Victorian complexes consist of various phenocrysts in a quartzo-feldspathic groundmass of rhyolitic composition (Edwards 1956). Quartz is the dominant phase, along with K feldspar (Or_{60} to Or_{75} in the rhyolitic rocks) and zoned plagioclase (An_{35}-An_{55} in the rhyodacites, An_{10}-An_{60} in the rhyolites) (Birch *et al.* 1977).

The ferromagnesian assemblages are typically S-type, dominated by biotite-orthopyroxene ± garnet in the rhyodacites and biotite ± garnet ± cordierite in the rhyolites (Birch *et al.* 1977). Iron-rich garnets are widespread and may be grouped on the basis of their zonation and composition (Birch & Gleadow 1974, Birch 1975, Clemens 1981). Iron-rich cordierite is present in the Rubicon, Ryans Creek and basal Strathbogie Rhyolites, while a more magnesian cordierite occurs in some of the rhyodacites (Dudley 1971). Biotite is more iron-rich in the rhyolitic rocks and orthopyroxene is generally hypersthene. The Toombullup 'Rhyodacite' contains the most diverse ferromagnesian assemblages, with biotite, several garnet types, two varieties of hypersthene (R. Dudley pers. comm.) and fayalite (Brown 1961, Clemens 1981). The western and eastern acid volcanic belts (including the Jemba Rhyolite) apparently do not contain these diverse ferromagnesian assemblages. More acid rocks in these belts normally carry biotite as the only mafic phenocryst.

MAGMA ORIGIN

In his discussions of the various acid volcanic complexes, Hills concentrated on their structural development rather than the origins of the magma. In his 1959 paper, he appealed to a single parent magma of acid-intermediate composition for all the complexes, but suggested that it was generated elsewhere and injected beneath the region. Hills regarded the late Middle Devonian Woods Point Dyke Swarm, chiefly of diorites and lamprophyres (Hills 1952) as 'fore-runners of an advancing wedge of magma moving from the east to the northwest'. He considered that differentiation in this magma body had produced the vertical gradation from rhyolite to 'dacite' and that the parent magma was very fluid (presumably to enable it to erupt as 'lavas'), free of xenoliths and was crystallising intratellurically when it erupted. Edwards (1937, 1956) had discussed the likely origin of the parent magma for the quartz diorites, granitic intrusions and lavas of eastern Victoria in terms of assimilation of argillaceous crustal rocks by basaltic (tholeiitic) magma, followed by crystallisation differentiation. White (1954) proposed widespread assimilation of alumina-rich sediments and thorough mixing of large amounts of contaminated basaltic magma rising slowly through the crust. The idea of dacitic magma injected beneath the region was still current in the mid 1960s, judging by the conclusions reached by Valiullah (1964) in his study of the rhyolite-dacite suite.

Over the last 10 years, the more intensive investigation of the chemistry and mineralogy of the central Victorian volcanic-intrusive complexes has resulted in a general consensus view that the parent magmas were anatectic in origin (Phillips *et al.* 1981). A number of lines of evidence, some already referred to, indicate that the parent rocks were broadly pelitic to quartzo-feldspathic metasediments. The general conformity of the major and trace element parameters with so-called 'crustal' values, the peraluminous nature of the rocks (most are corundum/hypersthene normative), their overall 'S-type' character, and initial Sr^{87}/Sr^{86} ratios of at least 0.710, (Brooks & Leggo 1972, McDougall *et al.* 1966), all suggested derivation of magmas from an evolved crustal source region.

Conditions under which the partial melting took place have been investigated using evidence from experimental work on natural granite compositions (e.g. Clemens & Wall 1979, 1981) and partition relations within the ferromagnesian suite (e.g. Clemens 1981, Birch & Gleadow 1974). Subtle differences in chemistry and mineralogy between individual complexes in central Victoria reflect variation in the nature of the source rocks and the conditions of melting. Nevertheless, the data suggest pressures and temperatures at least as high as 4-6 kbar and of 800-900°C and water-undersaturated conditions for magma genesis (e.g. Phillips *et al.* 1981, Clemens & Wall 1979). These are equivalent to depths of 17-25 km, indicating very high geothermal gradients.

Figs 12, 16-19, 21-23 — 12, vitroclastic textures within the basal rhyolite of the Violet Town Volcanics. 16, well preserved flattened shards in the Ryans Creek Rhyolite, 5 km east of Tatong. 17, vitroclastic textures in a specimen of the Wellington Rhyolite (NMV E10807), from Shanty Hollow, near Mt. Kent. The shards are replaced by a chloritic alteration product. 18, part of a flattened pumice fragment in the Wellington Rhyolite (NMV E10830). 19, specimen of Wellington Rhyolite (E10804), altered but showing occasional cusp-shaped fragments, indicative of original glass shards. 21, eutaxitic texture in the basal zone of the Jemba Rhyolite. The small pumice fragments are moderately flattened. 22, well preserved, contorted, flattened devitrified glass shards in the basal zone of the Jemba Rhyolite. 23, dense welding textures in the groundmass of a specimen of the Thorkidaan Volcanics (NMV E10706).

Note: Field of view is 0.9×0.6 mm in Figs. 12 & 16. Field of view is 3.5×2.3 mm in Figs. 17-19, 21-23.

There are few published interpretations of the origin of magmas for the acid volcanic belts in eastern or western Victoria. However, the distinctive major and trace element chemistry of the Jemba Rhyolite was attributed by Oates and Price (1983) to partial melting of refractory crustal material, from which granitic melts had previously been removed.

There are three possible origins for the fundamental transitional chemical variation shown by the Victorian acid magmas. These involve either a progressive separation of refractory phases from a granitic liquid of 'minimum melt' composition, a fractionation model involving products of magmatic crystallisation (including a degree of volatile transfer) or progressive partial melting in which removal of melt fractions becoming less silicic and more mafic took place. Given the size of the source region and the volume of magma produced, all three processes probably contributed to varying degrees.

The trigger for partial melting is uncertain in most cases, although it may well have been initiated by the diapiric upwelling, at various intervals throughout the early to middle Palaeozoic, of mantle-derived basic magma into the lower crust (Clemens & Wall 1981, Phillips *et al.* 1981). Basic rocks, admittedly in volumetrically minor amounts, are associated with many of the acid volcanic belts in the east. For example, basaltic rocks occur within the Snowy River Volcanics and the Wellington Rhyolites. An infaulted belt of mainly andesitic rocks of uncertain age (the Bumble Creek Andesites) is associated with the Thorkidaan Volcanics (VandenBerg *et al.* 1981). A dyke swarm, ranging from dioritic to doleritic, preceded the emplacement of the Jemba Rhyolite (Brooks & Leggo 1972). In central Victoria, the Woods Point Dyke Swarm, with rock types ranging from intermediate to ultrabasic (Hills 1952), was emplaced immediately prior to the main acid volcanic episodes, while basaltic andesites are represented within the Cerberean Cauldron sequence.

The generation of acid-intermediate magmas across Victoria throughout the early to middle Palaeozoic must be considered in relation to the complex crustal processes affecting the region during that time. For the Silurian to Lower Devonian magmas in eastern Victoria, Richards and Singleton (1981) suggested that partial melting took place below an island arc. This influenced the tectonic pattern, chiefly by protecting the sedimentary fill between it and the shield to the west, from the Late Ordovician until the Early Devonian. Acid magmas were then generated in both the west, where they are of mixed S and I-type, and in the east, where they are dominantly I-type (I. A. Nicholls pers. comm. 1982), even though these fall to the west (i.e., S-side) of the S-I line projected from New South Wales (Chappell & White 1976).

Crawford (1983 and in prep.) significantly extended the model, in both time and space, in an attempt to resolve the apparently contradictory situation in which oceanic lithosphere, now represented by the Victorian Cambrian 'greenstone' belts (Fig. 1), is associated with

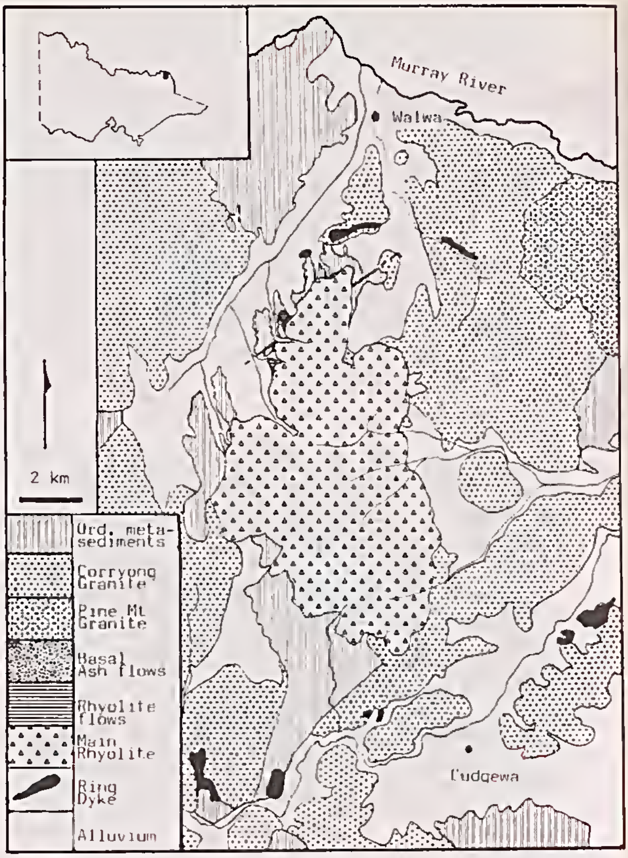

Fig. 20—Geological map of the Jemba Rhyolite (after Leggo 1964, Oates & Price 1983).

crustal thicknesses of a 'continental' scale (35-50 km) across Victoria (Cleary 1973, Gibson *et al.* 1981, Rickard & Ward 1981, Finlayson *et al.* 1980, Finlayson & McCracken 1981). The Crawford model invokes a series of island arcs and backarc basins developing eastwards across Victoria from the late Precambrian to the early Palaeozoic. The culmination of progressive westward subduction during this period was the underthrusting from east to west of thinned continental margin sialic crust, leading to overall crustal thickening and the generation of acid and intermediate magmas. This model would allow for the fact that estimates of the thickness of the Palaeozoic sedimentary cover (Cambrian-Late Devonian) across Victoria are neither sufficiently large (less than 15 km) nor reliable to support a magma origin by partial melting of the base of the sequence. Instead, an attenuated wedge of high grade Precambrian metasediments, beneath the Cambrian greenstones, and more or less continuous across Victoria, is the more likely source region (Clemens & Wall 1979, Phillips *et al.* 1981). Such a crustal thickening process, with its associated increased thermal gradients, could provide an alternative mechanism for anatexis. A logical extension of such a model would be to relate, in more detail, the various stages of crustal reorganisation to dated episodes of acid-intermediate magma genesis

Fig. 24—Pebble of rhyolite showing eutaxitic textures, from the Permian glacial till at Derrinal, Victoria. Specimen is 16 cm long (NMV E10733).

across Victoria. This would include the central Victorian complexes, which at present appear to be inexplicable in terms of an island arc-subduction zone model.

CONCLUSIONS

Since the pioneering efforts of E. W. Skeats and E. S. Hills, the Palaeozoic acid volcanic complexes have been recognised as one of the major features of Victorian geology. Whereas, in the period up until 1960, their significance was discussed in terms of structural features and stratigraphy, the last twenty years have seen their chemistry and mineralogy generate considerable interest. There is little doubt that the Victorian acid volcanic rocks, and in particular their ferromagnesian assemblages, provide a key to understanding some of the processes by which metasedimentary sequences become acid magmas. Hills' devotion to a wide variety of geological themes has seen him have little direct involvement in the second stage of the overall study. Nevertheless, the petrographical, mineralogical and geochemical features of the acid volcanics cannot be studied in isolation, without reference to a stratigraphic sequence or a structural model. Hills' role in establishing the most significant sequences, developing the cauldron subsidence model and encouraging studies in other complexes was fundamental to the present state of knowledge.

The principles of ash-flow volcanism and the criteria by which it is recognised have still not gained universal acceptance within Victoria. This need not be due to entrenched attitudes, but to a failure of those aware of the contemporary developments to communicate them adequately. The problem is best illustrated by misuse of terminology, such as when a sequence is said to consist of 'rhyolite, tuffs and ignimbrites'. This is not the least of the challenges confronting those working locally in the field of acid magma genesis.

ACKNOWLEDGEMENTS

I am grateful for the critical comments of Drs. A. J. W. Gleadow, T. A. Darragh and I. A. Nicholls in reading the original manuscript of this review. In addition, Dr Nicholls contributed unpublished information on the volcanic rocks in the eastern belts, particularly the Mitta Mitta Volcanics.

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